

# **Expert System For Mine Burial Prediction**

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## **LONG-TERM GOALS**

The degree of mine burial is a crucial factor in Mine Counter Measure (MCM) mission planning, having a significant effect on sensor range and effectiveness. The ultimate goal of this project is to provide an mine burial prediction fleet aid for operational Navy MCM decision making that incorporates recent research in burial mechanisms and seafloor sediment behavior. This predictive tool should provide an accurate assessment of the uncertainty inherent in these complex processes and properties in order to allow realistic risk evaluation.

## **OBJECTIVES**

The objective of the present effort is to enact an expert systems approach to mine burial prediction. The current generation of deterministic, physics-based models provide only a partial representation of the total complex burial processes. In addition, the MCM planner often has limited knowledge of the mine deployment and environmental conditions. Therefore, a probabilistic predictive structure is appropriate. An expert system to synthesize the current state of knowledge on mine burial behavior is being developed which incorporates extant models for mine burial prediction as well as improved physics-based models currently under development in the ONR Mine Burial Program (ONR-MBP). The expert system approach also makes use of statistical relationships derived from field observations obtained from ONR-MBP projects.

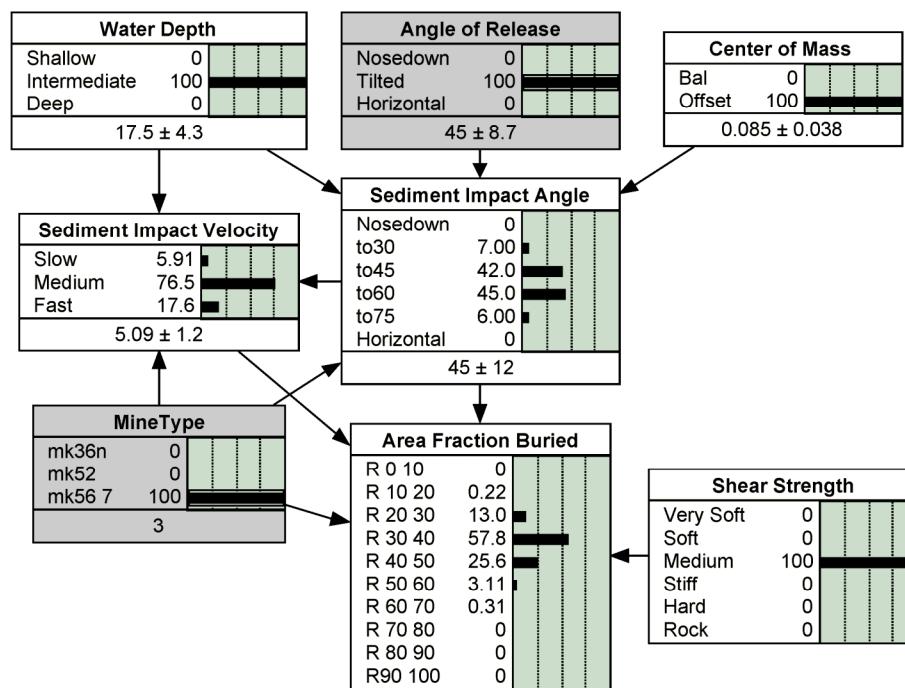
A major goal of this effort has recently been set forth in a draft ONR/NAVO Technology Transition Agreement (TTA) to provide for transition of the MBESM into NAVO's Warfighting Support Center to enhance their capability to develop products in support of Fleet MCM operations. This goal will be accomplished via collaboration with Nathaniel Plant at NRL-SSC through a number of specific efforts: to cast the probabilistic results of the MBESM in a form suitable for NAVO use; to exercise the MBESM to provide predictions for situations of specific interest to NAVO; to compare the MBESM predictions to those provided by current NAVO doctrine; and to assist NAVO in evaluating the expert system's effectiveness.

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## APPROACH

The Mine Burial Expert System Model (MBESM) has been formulated as a Bayesian probabilistic structure. Models which predict burial by impact or by scour have been developed using the Bayesian software Netica™ (NorSys, 2002) and are implemented as Bayesian belief networks, which represent causal influences among variables as linked conditional probability tables (CPTs). For the current implementation of MBESM, most of the CPT values were filled in from Monte Carlo explorations using established physics-based models. Versions of the models were recoded in Matlab, with additional Matlab shells that exercise the models repeatedly throughout their domain space. The CPTs also incorporated the results of field and laboratory data, as well as assessments from experts in the field. Output burial predictions result from the joint probabilities obtained by applying Bayes Rule to the preceding input nodes in the MBESM network.

The Netica software allows the user to explore the results of different burial scenarios using an user-friendly graphical interface. In this package the user specifies input distributions that characterize the available knowledge of the state of the mine deployment and environmental conditions. An example is shown in Figure 1 for the impact burial portion of the MBESM network. This example illustrates a high knowledge level scenario, where each of the inputs was known with certainty within the assigned input bin categories, resulting in a fairly constrained burial probability distribution.



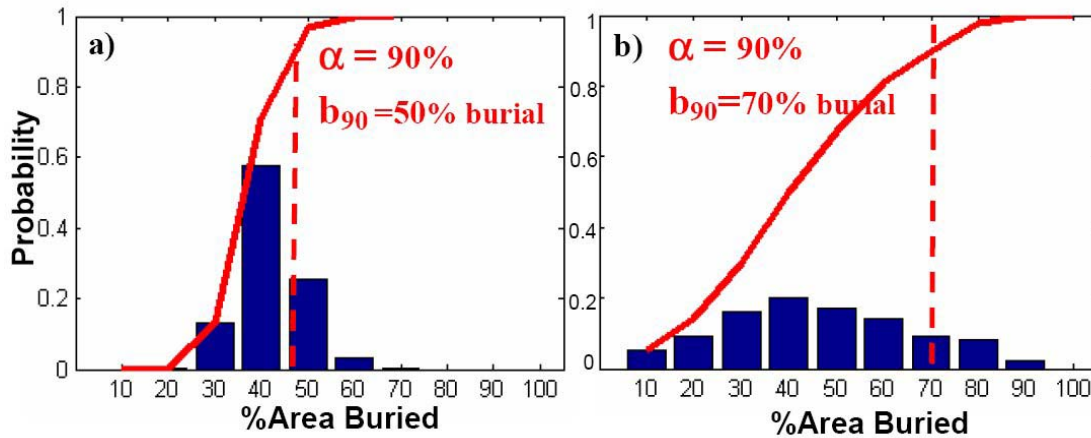
**Figure 1. Example of impact prediction from the Mine Burial Expert System Model (MBESM)**  
**[For Mark56 mines dropped into medium shear strength sediments, most (96.4%) will be buried**  
**between 20 to 50%, with the mode between 30 to 40%.]**

While the NETICA GUI provides an excellent environment for in-depth exploration of mine burial behavior, an automated approach is more useful for the minehunter tasked with planning MCM operations over a large geographic area. A batch-mode wrapper for running the MBESM is under development using the NETICA JAVA-API (Application Program Interface), which embeds the Bayes net functionality within a Matlab program that can manage the repetitive I/O requirements, such as interfacing with sediment databases and producing multiple burial predictions in map form.

Since the prediction of mine burial upon impact requires geotechnical information not currently available in the NAVO sediment databases, an interim empirical mapping has been developed which relates the available textural (grainsize) information into an estimate of the probability distribution of shear strength (see the annual report by N. Plant, CGPLANT for FY-04). This interim model was updated to include an improved marine geotechnical database compiled by Bennett et al. (2004) at SeaProbe, Inc.

The MBESM produces a burial prediction in the form of a probability distribution, which provides an assessment of the real-world uncertainty inherent in current modeling and database information. In order to transition the MBESM to NAVO, a method is required to consolidate the probabilistic predictions into a measure that is compatible with existing Navy operational procedures. Towards this end, a cumulative probability formulation has been developed (N. Plant, 2004).

In operational use, a risk threshold,  $r_t = 1 - \alpha$ , can be specified, where  $\alpha$  is the cumulative probability, so that  $r_t$  is the probability that the minefield burial is underpredicted. An example of conservative risk might be  $\alpha = 99\%$ , indicating that in only  $r_t = 1\%$  of the time can the mines be allowed to be buried more than forecast by the model. Then, a cumulative burial prediction statistic,  $b_\alpha$ , is the value of burial percentage where the cumulative sum of the probability distribution is equal to  $\alpha$ . The calculation of burial prediction  $b_\alpha$  is illustrated in Figure 2 for two cases with the same risk threshold, but different burial distributions. In Figure 2a,  $\alpha = 90\%$  is required of the burial distribution predicted by the impact scenario shown in Figure 1, resulting in a burial statistic  $b_{90} = 50\%$ . Thus for this case there is only a 10% risk that any mine is more than half buried. In the second example, Figure 2b, the output distribution predicts approximately the same mean burial, but is spread more broadly, due to increased uncertainty in the inputs, so that a  $b_{90} = 70\%$  burial is required to accommodate a risk tolerance of 10%. There is an intuitive connection between increased uncertainty and increased risk; e.g., in Figure 2b, if half-buried mines are of concern, the minehunter would have to tolerate a much higher risk.



**Figure 2. Burial probability distributions predicted by the MBESM impact model**

## WORK COMPLETED

The MBESM structure for the IMPACT network has been redesigned to more accurately reflect the physical relationships revealed from field and laboratory observations obtained from ONR-MBP efforts dating from 2000 through 2002. The Conditional Probability Tables were recreated using an updated version of the Navy model IMPACT28 which had been modified to reproduce the mean results of the field data (Rennie et al., 2004), following extensive validation and sensitivity analyses.

Validation of the physics-based scour model used as a basis for the Bayesian network was extended to include recent field data from the Indian Rocks Beach (IRB) field program in winter of 2003 resulting in the reformulation of the friction factor. Continued sensitivity analysis allowed refinement of the CPT bin ranges with more accurate response at lower stress levels and elimination of unnecessary high levels, as well as the simplification of the Bayesian network structure. Intermediate nodes for the ambient bottom stress from tidal currents and from waves are now retained to allow the rapid incorporation of new mine shape behavior results.

A Matlab-callable Java-API wrapper was developed for automated batch-mode calculations of the NETICA Bayes network predictions.

The interim shear strength regression model was updated to include an improved geotechnical dataset and reformulated to produce a predicted lognormal probability distribution of shear strength for a given NAVO sediment category. This form retains a quantitative measure of the uncertainty in the relationship.

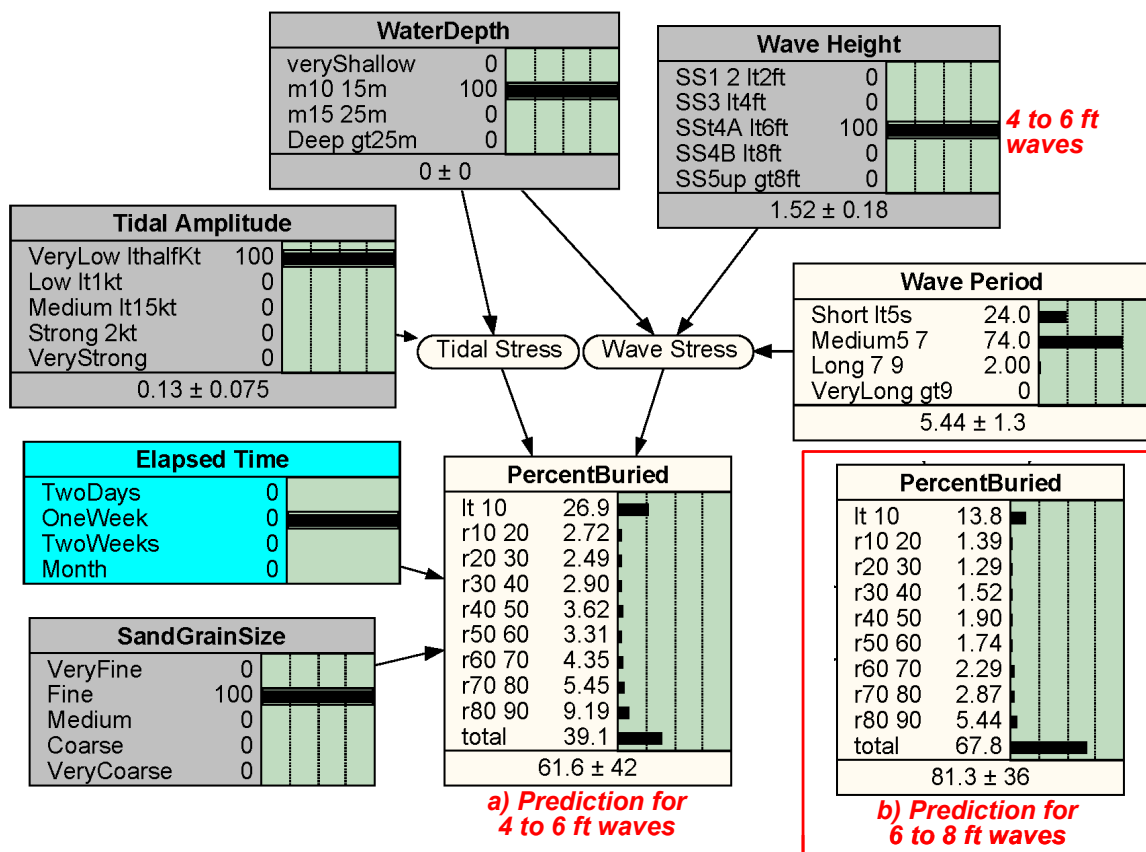
An inter-comparison example between the NAVO doctrinal predictions and the MBESM output was completed for the area offshore of Corpus Christi using the cumulative probability risk formulation (N. Plant, 2004).

An error budget analysis has been undertaken to identify the potential sources of uncertainty in the burial modeling procedures and to quantify the usual magnitudes of these sources. Various methods for reporting error as distinct from natural variability have been explored, one illustrated by the green

error bars on Figure 2b. A version of the Bayesian network is under evaluation that directly incorporates the PDF of the residuals from the model validation as an uncertainty factor.

## RESULTS

The primary result of the past year's effort have been an improved understanding of the sensitivity and uncertainty sources for modeling mine burial processes. Figure 3 illustrates the revised Bayes network for the prediction of burial of cylindrical mines by scour. The water depth, tidal currents and sediment grain size bins are set to represent the shallow-water fine-grained site at the Indian Rocks Beach field experiment, with the distribution of wave periods derived from a histogram of observations taken during the winter of 2003. The network predicts, for wave heights between 4 to 6 ft, that after a week less than 40% of the mines would be buried. Shown in the inset panel b is the prediction for somewhat larger waves, ranging from 6 to 8 feet, where almost 70% of the mines would experience total burial. This sensitivity reflects the measurements at IRB, where the deployed mines were observed to scour rapidly only during times when the wave heights approached 2 meters (> 6 feet). The spread in the output prediction is due largely to the sensitivity of the effects of waves over the water depth bin ranging from 10 to 15 meters.



**Figure 3. Bayes Net for the prediction of scour at IRB**  
*[ Two output prediction distributions are shown, a) forced by 4 to 6 ft waves, and b) forced by 6 to 8 ft waves, where significantly more burial occurs.]*

## IMPACT/APPLICATIONS

The goal of the MBESM is to provide state of the art mine case burial information in a form that can be used by MCM tactical aids to improve the ultimate prediction of the crucial parameter  $\mu$ , the fraction of undetectable mines in a proposed mine hunting scenario. The expert system acts as a repository for additional knowledge as the ONR-MBP projects increase understanding of mine burial processes. The Bayesian structure also provides a mathematical formulation for the synthesis of the uncertainty inherent in both input data and model physics. The quantitative error estimation provided by this approach will be an valuable addition to the MCM planning process.

## TRANSITIONS

A technology-to-operations Technology Transition Agreement has been drafted between the ONR Mine Burial Prediction (MBP) program and the Navy Oceanographic Office (NAVO) in which the plan for the development, testing, and implementation of the MBESM is laid out. In a phased approach to evaluating the MBESM, NAVO will use it in-house to evaluate its effectiveness as part of their normal operations. Discussion are on-going with Ronald Betsch, Mark Null and Peter Fleischer at NAVO, facilitated by Nathaniel Plant of NRL-SSC, on the best method to integrate the MBESM with the NAVO databases.

## RELATED PROJECTS

The MBESM utilizes results from several other projects within the ONR Mine Burial Prediction Program (<http://www.mbp.unh.edu/>). Analysis of several field observation datasets have been incorporated (Valent et al., 2002, Richardson and Traykovski, 2002). Refinements of the scour model formulation from VIMS (Freidrichs et al., 2004) were included in the most recent version. Advanced models of mine hydrodynamics have been received from the Naval Postgraduate School (Chu et al., 2002) and from researchers at MIT (Yue et al., 2003) and are currently under evaluation.

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